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RESISTIVITY MEASUREMENTS UPON ARTIFICIAL BEDS

BY

JOEL H. SWARTZ

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BY J. H. Swartz[2]

INTRODUCTION

During a series of resistivity measurements carried out in 1929 and 1930 a number of questions arose concerning the effect of topography on the character of the curves and the depths attained, the ratio of true depth to certain radii interpreted as representing depth, etc. To answer these questions it was decided to undertake a series of experimental investigations on artificial strata. It is the purpose of the present paper to present the results of the studies thus undertaken.

ACKNOWLEDGMENTS

The writer wishes to express his appreciation of a grant from the Rockefeller Fund of the University of North Carolina which permitted the construction of the artificial strata used in this study and the purchase of the materials required for them. Acknowledgment is also made of indebtedness to F. W. Lee and the U. S. Bureau of Mines for the use of direct-current instruments and apparatus, and to D. D. Carroll of the University of North Carolina for his kind permission to use his land for the construction of the hole and its contained artificial strata.

The writer wishes especially to express his thanks to W. T. Holland, of the University of North Carolina, for assistance without which the experiments could not have been completed, and to J. H. Watkins for invaluable aid. It is further a pleasant obligation to acknowledge the help given him in the construction of the experimental block by I. L. Martin, E. R. Scott, W. H. Hadley, and C. S. Maurice.

METHOD OF INVESTIGATION

A series of artificial beds was built up under conditions as nearly like those obtaining in actual field work as possible. In order to simulate such conditions accurately it was decided to place the beds in a large hole dug in the ground, thus doing away as far as possible with distortions of the electric field due to boundary conditions. It was further necessary to obtain a place free from pipes or other conductors and one where the walls of the hole would be or could be made impervious so that fluids placed in the artificial strata could not leak out into the surrounding soil nor pass in that way from one bed to another. It was thus necessary to find a location where the subsoil was an impervious clay or where an ample supply of such clay was available. After an extended search an ideal locality was found where a diabase dike of Triassic age had weathered to a very impervious clay.

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[1] The Bureau of Mines will welcome reprinting of this paper, provided the following footnote acknowledgment is used: "Reprinted from U. S. Bureau of Mines Information Circular 6445."

[2] Senior geophysicist, U. S. Bureau of Mines.

At this locality a hole 15 feet long, 12 feet wide, and 3 feet deep was dug. The hole was made large so that practically the whole of each potential hemisphere measured would lie within the hole in the artificial strata on which tests were being made. Sand from a nearby stream bed was used to form pervious beds for oil and salt water horizons. The impervious clay from the hole was used to seal off roots, animal burrows, and other openings in the walls and to form impervious beds separating the pervious strata from each other.

After the hole was dug it was divided into a series of 1-foot squares by a coordinate system, as shown in Figure 1, and the exact elevation of each intersection in the clay base was determined by transit. The beds described in greater detail below were then placed in the hole. The sand strata were formed by shoveling in the stream sand, which was then spread around and brought to exact level by packing, scraping, and filling, the final level being checked by transit.

Much difficulty was experienced with the clay layers separating the sands. The clay dried rapidly to a hard, brick-like mass which had to be broken up and moistened several hours before use. The amount of water used required rather careful adjustment since too much water made the clay too soft to retain its shape, whereas too little water left it too hard to permit working. Attempts were made at first simply to throw the clay in the hole and tamp it into place as lightly as possible. This procedure failed because it was either necessary to make the clay too soft to retain its shape and position or else to cause considerable damage and displacement in the underlying sands. It was finally found most satisfactory to take large chunks of the clay softened enough to be very slightly plastic while still retaining their toughness and tenacity and to chop them with a hatchet to the desired thickness and shape. The blocks so obtained were carefully fitted together and any spaces left filled by semiliquid or very soft clay. The top of each clay bed was carefully divided into 1-foot squares as before, and the exact levels of all intersections were determined by transit. Three sands were thus built up, separated and capped by layers of clay.

When the surface layer of clay had been added the hole was divided crosswise into two halves. In one half the surface was kept approximately level. In the other half a ridge-like mound 10 inches high was built up in the center. The shape of the surface is best seen on the topographic map, Figure 1.

The following is a list of the strata employed:

Clay 1. Base of hole, slanting upward to a central ridge. Elevations ranged from 0.00 at the north and south ends to +0.57 in the center (All elevations in hundredths of a foot above the lowest point of hole) See Figure 2.

Sand 1. This sand ranges from +0.45 at the edges to +0.82 in the center. It is divided into three parts. In the center an 18-inch wide lens of oil-saturated sand is separated by 3-inch walls of impervious clay from the wet sands on either side. On the north or "hilly" side of the hole this sand is filled with salt water carrying 30 pounds of

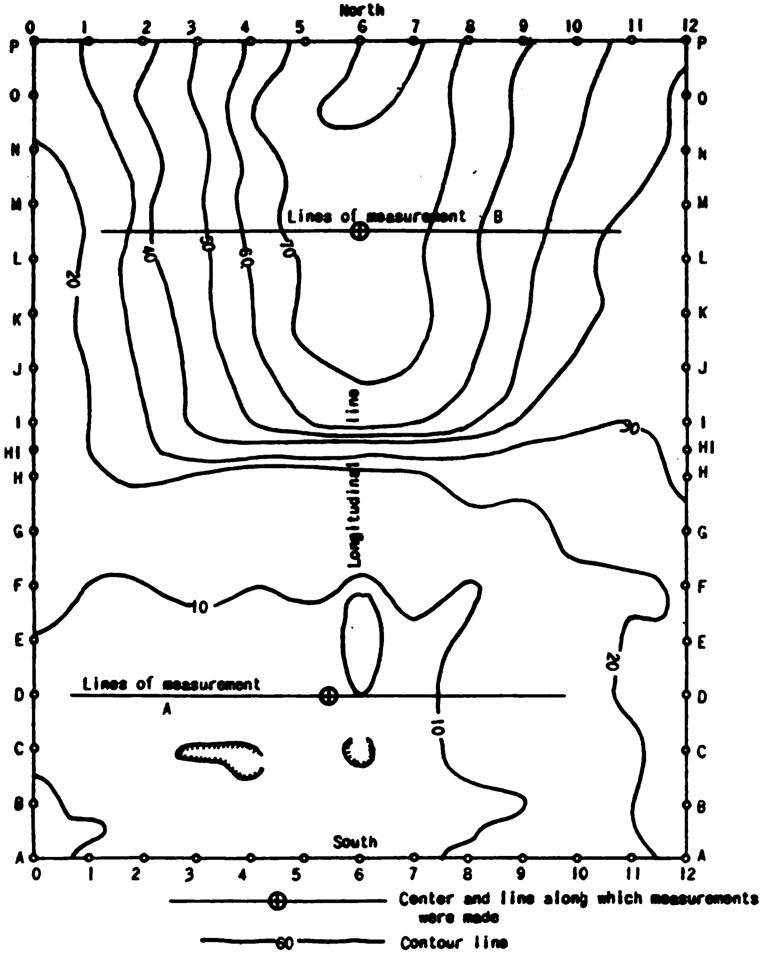

Figure 1.- Topographic map of surface of completed experimental block (top of Clay 4)

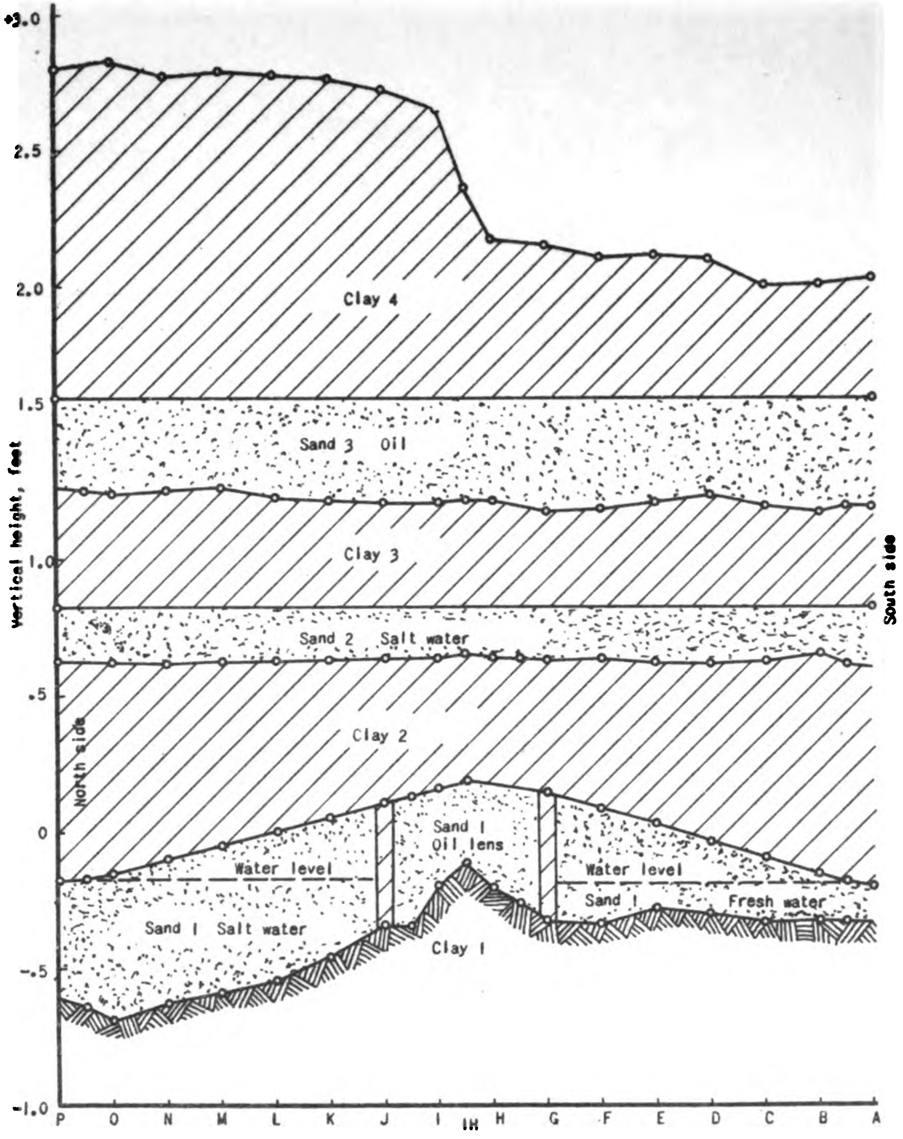

Figure 2.- Medium longitudinal section through experimental block

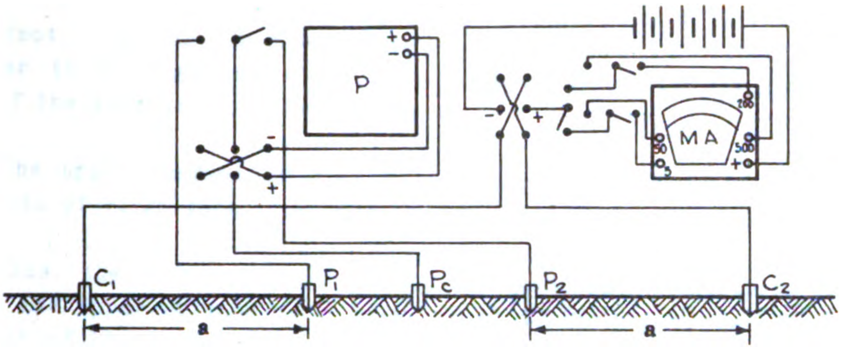

Figure 3. – Connections for Lee's method. C_1 and C_2, current stakes; P_1, P_2, and P_c, potential pickups; P, potentiometer; M A, the milliammeter

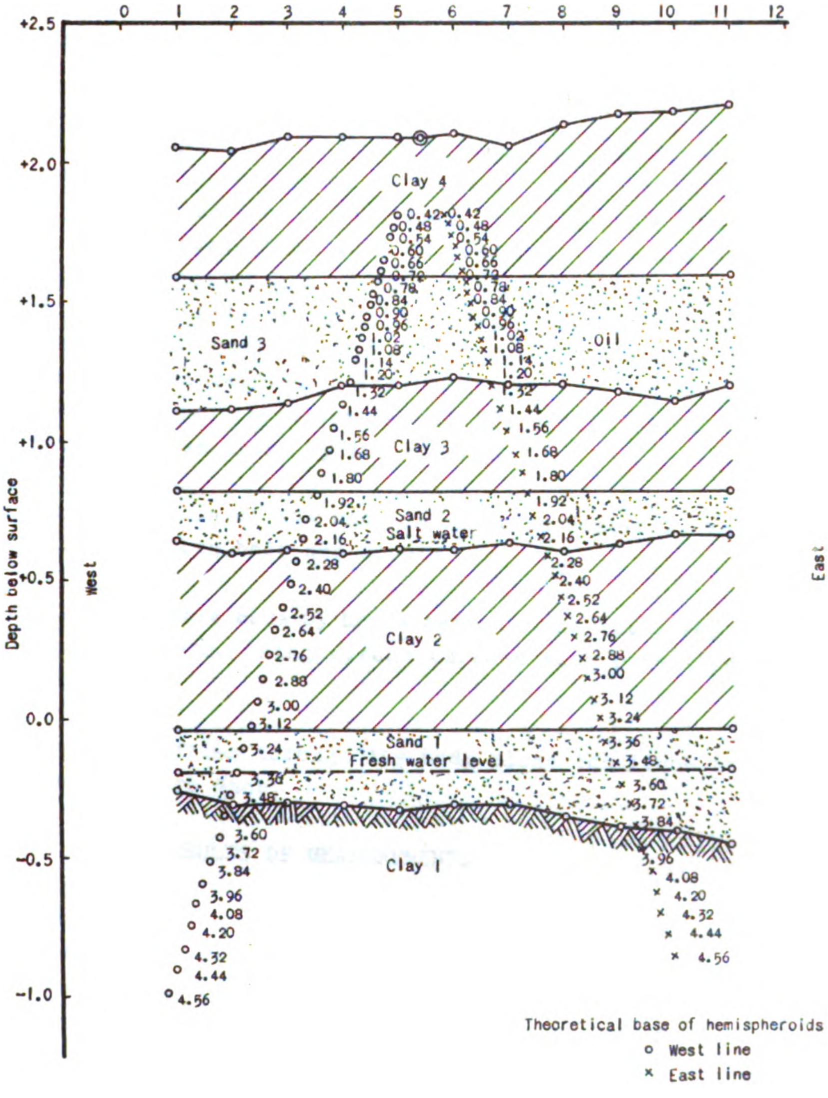

Figure 4.– Vertical section through the flat side of the experimental block along line of measurement A

salt dissolved in 150 gallons of water and filling the sand to a depth of +0.47 foot. On the south or "flat" side the sand is filled with fresh water to a height of +0.45 foot. Above these two levels in either half the sand is dry; See Figure 2.

Clay 2. The upper surface of Clay 2 is horizontal and stands at an average level of +1.29 feet above the lowest point in the hole.

Sand 2. This, the first entirely horizontal sand, has a thickness of 0.20 foot, its upper surface at a level of +1.49 feet above zero (the lowest point of Clay 1, the clay base). This sand is filled throughout with salt water formed by dissolving 60 pounds of salt in 160 gallons of water.

Clay 3. Horizontal layer with its upper surface at an average elevation of +1.89 feet.

Sand 3. Oil sand. Horizontal layer of thickness 0.37 foot, with upper surface at elevation of +2.26 feet. Filled with 160 gallons of Bunker C oil, a heavy, black fuel oil with a gravity of about 14° B.

Clay 4. Final clay cap. Upper surface shown on topographic map, Figure 1. Elevation of lowest point of surface, which serves as zero point in Figure 1, is +2.67 feet. This clay had to be put on during a heavy rain, in order to protect as much as possible the underlying oil sand. As a result a considerable amount of oil oozed up into it, in some places through it, while being laid. These oil seeps were later blocked by adding clay and surface soil after as much of the oil-soaked clay as possible had been removed. A certain residuum of unremovable oil remains to cause some irregularities in the resistivities of the lower half of this clay, as shown by the curves.

The arrangement and position of the beds is shown in Figure 2, which gives a median, longitudinal section through both hole and strata.

Measurements on the beds were made by Lee's method of partitioning, Wenner's method and the single electrode probe method, using direct current with potentiometer and milliammeter.

Figures 4 and 10 give profiles through the beds along the lines in both hilly and flat sides on which measurements were made.

RESULTS OF MEASUREMENTS

Direct Current. Direct current was furnished by one to three radio B batteries. In view of the diminutive character of the beds and the correspondingly small intervals, 0.08 foot, between measurements the ordinary porous cup nonpolarizable electrodes were too large to be satisfactory. Electrodes which proved entirely satisfactory were made from ordinary porcelain tube insulators by closing the bottom with a little retort cement. A length of copper wire was placed inside, the whole filled with a concentrated solution of copper sulphate with an excess of copper sulphate crystals, and the top closed with a small cork. Because of the density of the porcelain it was found necessary to let the electrodes stand for a couple of weeks before use, to allow the walls to become saturated with the solution. For current electrodes, brass bolts 5/16 inch in diameter were used. The results of the individual experiments follow.

Lee's Method of Partitioning

The details of Lee's method have been adequately described elsewhere[3] and need not be repeated here. Figure 3 shows the electrical connections used. In Figures 5A and 5B are given the results obtained along line A in the application of this method to the southern or flat half of the experimental beds. The figures beside each point on the curve give the distances of the current stakes from the center stake for those points. Two curves are given, the 5A curve representing the line measured to the east of the center, the 5B curve that to the west.

We discuss first the eastern curve. Due to the dryness of the surface the curve starts at a comparatively high resistivity, 14,000 ohms per centimeter cube. This is followed by a rapid drop as the ideal hemispheres penetrate into deeper and more moist clay. This continues with minor fluctuations to a depth of 0.44 feet (current distance 0.66 feet). Beyond this point the curve rises rather rapidly to a maximum between points 1.20 and 1.32, though nearer the latter figure as shown by the shape of the curve. Turning to the diagram of the beds (fig. 4) we note that the base of Clay 4 is at a depth of 0.50 feet below surface. This at first sight appears to be slightly deeper than that indicated by the curve. As has already been pointed out, however, weather conditions made it necessary to cover the underlying oil sand so rapidly that a considerable amount of oil was caught in the lower part of Clay 4. The presence of this oil is clearly indicated by the fact that the rise toward the maximum begins at the shallower depth.

In Figure 4 the symbols (circles and cross marks) represent the theoretical position of the base of the ideal equipotential hemispheres measured for each position of the current stake, the distance of the current stake from the center for that particular point being given by the figures beside the symbol. Since these figures also identify the corresponding points on the curves they form a more convenient distinguishing mark than the depth and will hereafter be used for identification purposes instead of the depth.

The base of the oil sand in Figure 4 is exactly where indicated by the curve in Figure 5A, between the points 1.20 and 1.32 but much closer to 1.32. The sharp drop to point 1.44 is probably due to a small amount of water at the base of the oil sand. Below point 1.80 there is a slight increase in the steepness of the curve followed by a minimum at or near point 2.16. This coincides accurately with salt-water Sand 2 whose top, as seen in Figure 4, lies between points 1.80 and 1.92 and whose base lies just below point 2.16. Following a slight rise to 2.28 there is a rapid drop through moist clay to point 3.24, the base of Clay 2. Below this point lies Sand 1. As pointed out, this sand is filled with fresh water, but only to the level indicated in the diagram. Above this point the sand is dry, or relatively so, and hence has a higher resistivity. This is clearly shown by the increased resistivity at points 3.36 and 3.48 in the curve, Figure 5A. These two points are

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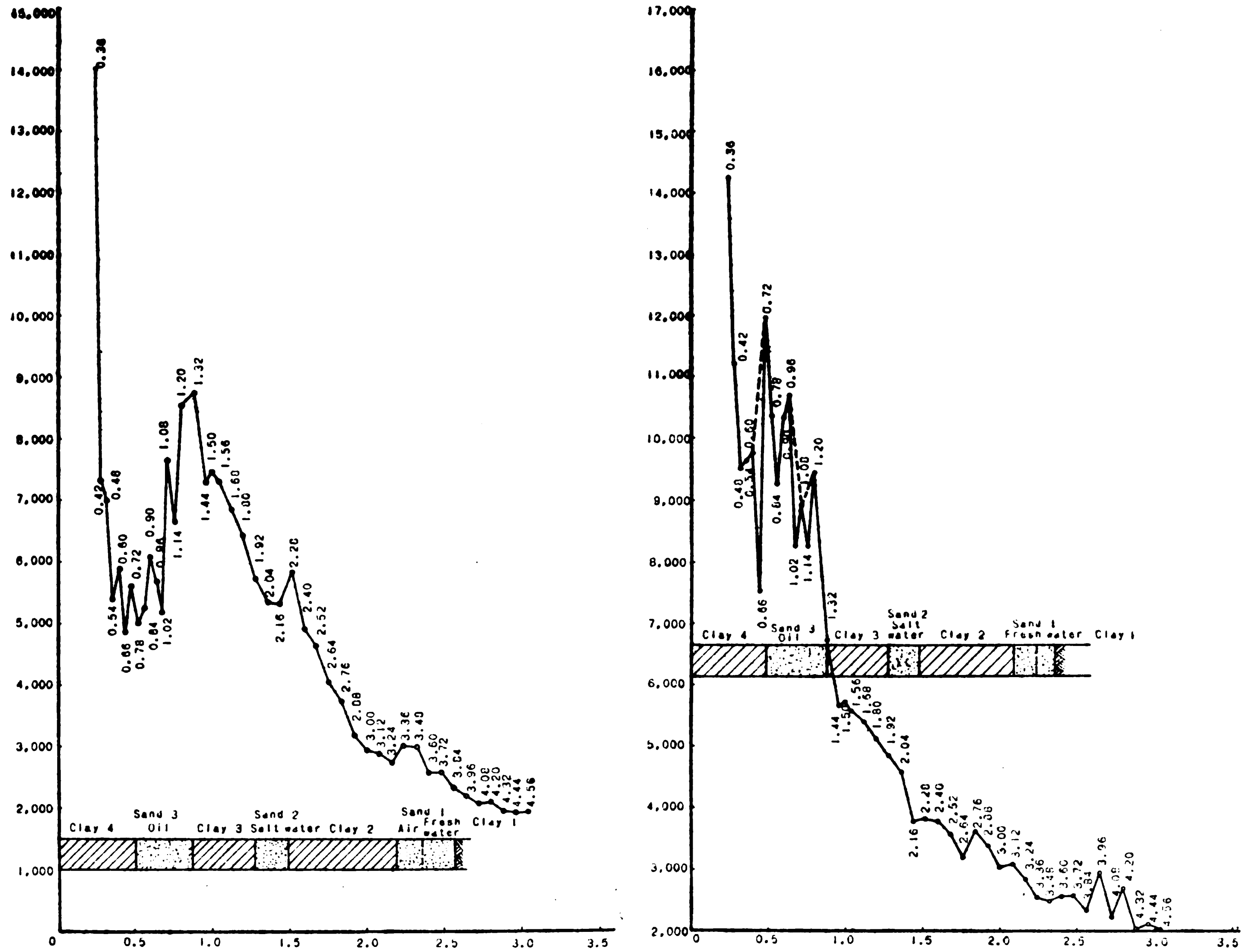
[3] - Lee, F. W., and Swartz, J. H., Resistivity Measurements on Oil-Bearing Beds: Tech. Paper 488, Bureau of Mines, 1930, 12 pp.

Swartz, J. H., Oil Prospecting in Kentucky by Resistivity Methods: U. S. Bureau of Mines Technical Paper, to be published.



A - East side

B - West side

Figure 5.- Curves obtained on flat side of experimental block by Lee's method of partitioning

exactly those shown in Figure 4 to be located in this upper dry portion of the sand. This is followed by a steady decline through the fresh-water filled portion of the sand and the underlying moist clay to 4.32, where the curve flattens out. The exact correspondence between the theoretical depths as indicated by the curve and the actual depths as measured in building the strata is striking.

Much the same characteristics are found in the west curve, Figure 5B. The break here is at 1.20 and is sharper, due very probably to a larger amount of water at the base of the sand on this side caused (a) by the greater slope to the west of the center and (b) by the fact that the east side of the oil sand was covered first, leaving the west side of the sand exposed to a heavy downpour of rain for a much longer time. The effect of the salt-water is first seen at 2.04 instead of 1.92. As shown in Figure 4, however, a displacement of only 0.01 foot would suffice to throw the 1.92 point up into the clay. Thus a slight drop in Clay 3, due to tamping, or a slight soaking of the salt water into the underlying Clay 2 would more than account for this apparent disparity.

In this curve also points 3.36 and 3.48 represent a minimum rather than a maximum. It is to be noted, however, that points 3.36 and 3.48 on this side, due to topographical differences at the surface, corrected for in locating these points in Figure 4, lie not in the dry part of the sand but below in that portion occupied by the fresh water.

Three points stand out from this study of the curves: (1) The insulating effect of the oil and short circuiting effect of the salt water do not prevent the registering of resistivity variations in the underlying beds (for instance, the "high" due to dry sand at 3.36 and 3.48 (fig. 5a) on the east line). (2) The depth at which a given resistivity change occurs is given with striking accuracy by plotting the apparent resistivity against a as here done (where a is one-third the distance between the current stakes and is calculated from the formula = 383 a E/I, in which I is the total current flowing in the circuit, and E is the potential drop between the pick-up electrode and the central electrode). (3) The depth reached must always be measured beneath the current stake, not beneath the center. This, of course, is due to the fact that the equipotential hemisphere on which the measurement is made surrounds the current stake, not the center. This factor will be further discussed at a later point.

Wenner's Method

If the central electrode in Figure 3 is disconnected and the potential drop measured between P and P we have the connections and method first suggested by Wenner. Figure 6 gives the results of a series of measurements made by this method about the center and along the line used for Lee's method above. While the curve shows the same general characteristics, the individual features are less pronounced. Thus the top of the oil sand, point 0.66, is much less clearly indicated, though the base of the sand, point 1.20, is still clearly drawn. The salt water sand at 2.16 is indistinct. The dry upper portion of Sand 1 does not show. The inferiority of this method when compared with Lee's method of partitioning is due to the fact that lateral changes in topography and to lateral variations in the stratigraphic character and structural position of the beds cause the two halves of the electric field to differ, often strikingly. In Lee's method each half is measured separately. In Wenner's method the two halves are averaged together and their individual characteristics thus concealed.

Single-Electrode Probe

A series of measurements were made at the same center using the method of the single-electrode probe, connections for which are shown in Figure 7. Two procedures were employed. In the first a series of concentric but overlapping hemispherical shells of regularly varying thickness were measured, the outer radius, a, being increased by a constant interval, in this case 0.08 foot, but always kept equal to twice the inner radius, as first suggested by Lee. In the second a series of concentric but contiguous, nonoverlapping hemispherical shells was measured, the shells having a constant thickness of 0.08 foot, both radii being increased by 0.08 foot between measurements.

Figure 8 gives the results of measurements made by the first method, that of overlapping shells of regularly varying thickness in which a always equals 2b. The interpretation of this curve is difficult. The rapid rise shown by the initial part of the curve would the rise begins is too shallow, even after correcting for the oil trapped in the base of Clay 4. The peak at a in Figure 8 can not represent the base of the oil sand, since the curve continues to rise to the point c; and there is no doubt, as shown by the other curves, that it should drop steadily after reaching the moist Clay 3. The maximum at point c would thus appear at first sight to mark the base of the oil sand. However, a comparison with Figure 5B, measured along the same line, indicates that peak e is perhaps even more likely to represent that point. In either case, however, the plotted depth is somewhat too great instead of too shallow.

There seems no doubt that the minimum, h, represents the base of the salt water Sand 2. If so, this constitutes a still greater discrepancy between plotted and true depth, the plotted depth being again too great. Thus the plotted depth is too shallow for the first part and two deep for the latter part of the curve. When one part fits, the other does not. The factor by which a, the outer radius of the shell, must be multiplied to obtain the true depth, is thus not a constant but a variable. Although it appears to decrease in value with depth, the data is insufficient to permit conclusions concerning the regularity or significance of this change.

Lee has pointed out that it appeared necessary to multiply the outer radius of the shell by 1.4 to obtain the correct depth. A similar factor appears in the charts given by Crosby and Leonardon . In both these cases a simple arrangement of two contrasting strata was involved. In the present experiment the stratal configuration is more complex, eight essential stratigraphic units being involved, resulting in a greater variation of the correction factor. It thus appears that with increasing stratigraphic complexity the equipotential hemispheres in the method of the single electrode probe are subject to such considerable and variable distortion that there remains no constant relationship between plotted and true depths. Since the relationship between the curve and the strata involved is a variable one, it becomes difficult to interpret it satisfactorily.

Shells of Constant Thickness

Figure 9 gives the curve resulting from the second procedure, the measurement of a

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4 - Lee, F. W., Joyce, J. W., and Boyer, Phil, Some Earth Resistivity Measurements: Information Circular 6171, Bureau of Mines, 1929, 16 pp.

5 - Leonardon, E. G., and Kelly, S. F., Some Applications of Potential Methods to Structural Studies: Am. Inst. Min. and Met. Eng., Tech. Pub. 115, 1929, 18 pp.

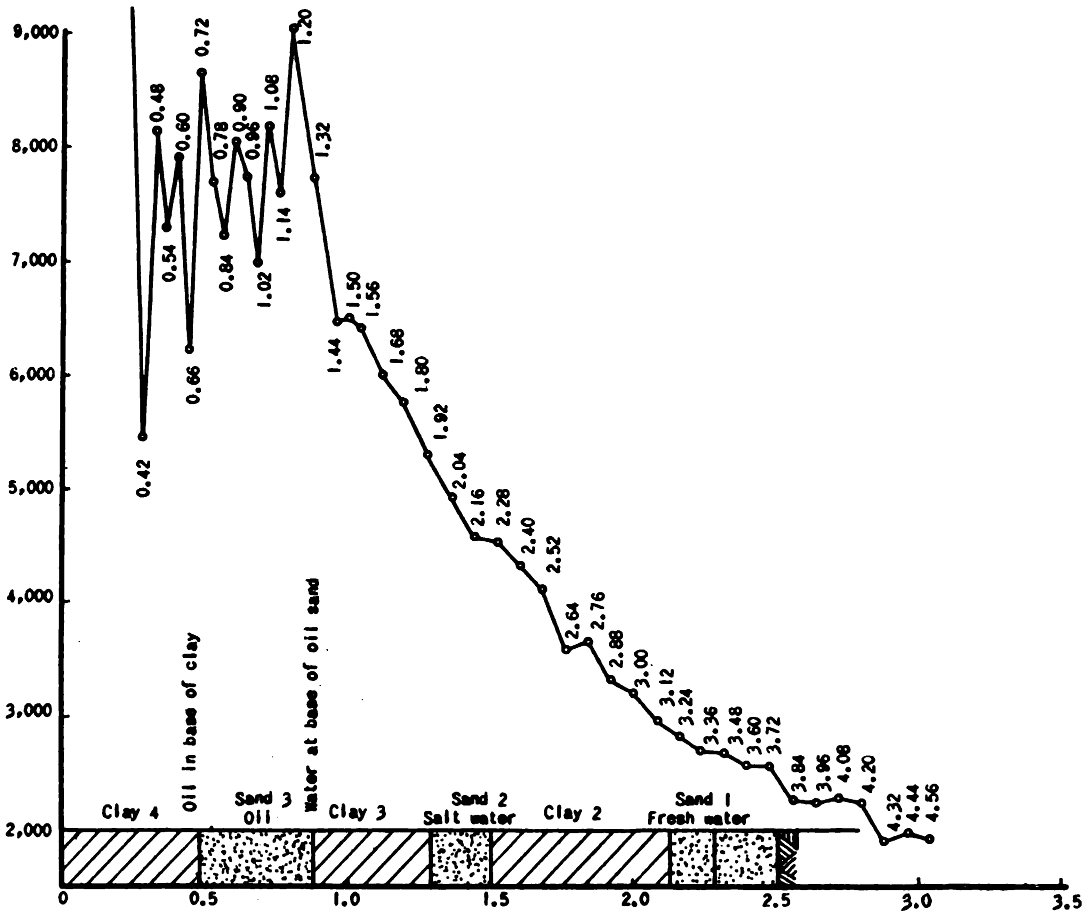

Figure 6.- Curve obtained on flat side of experimental block by Wenner's method

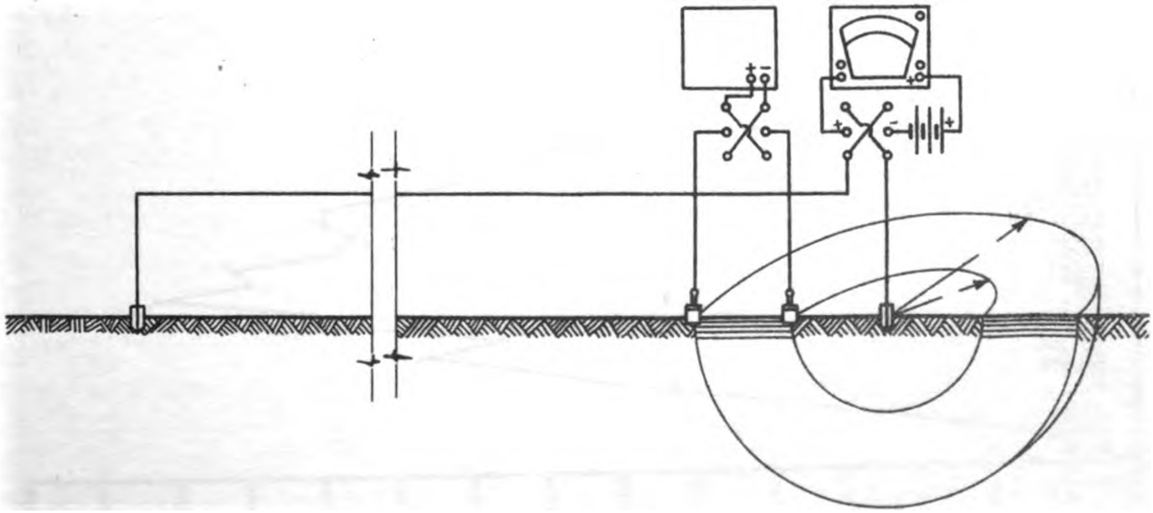

Figure 7. - Connections for the single probe method

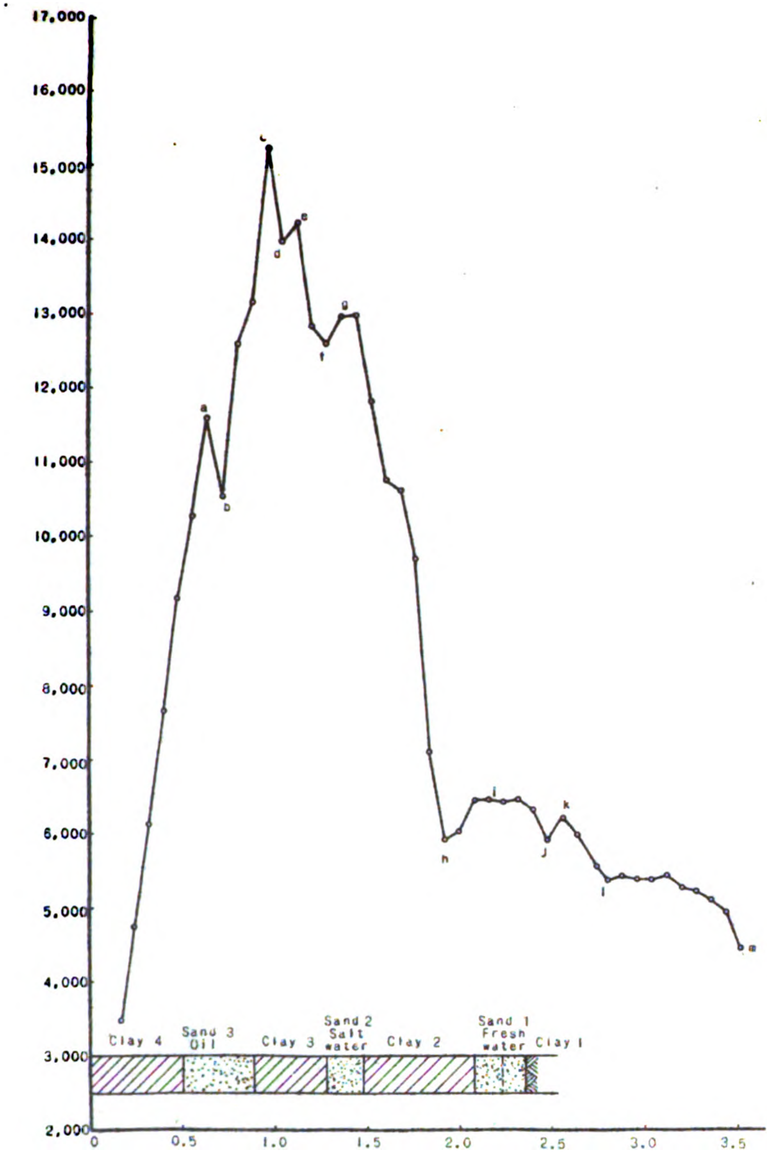

Figure 8.- Curve obtained on flat side of experimental block by the single-electrode probe, keeping a = 2b, as suggested by Lee

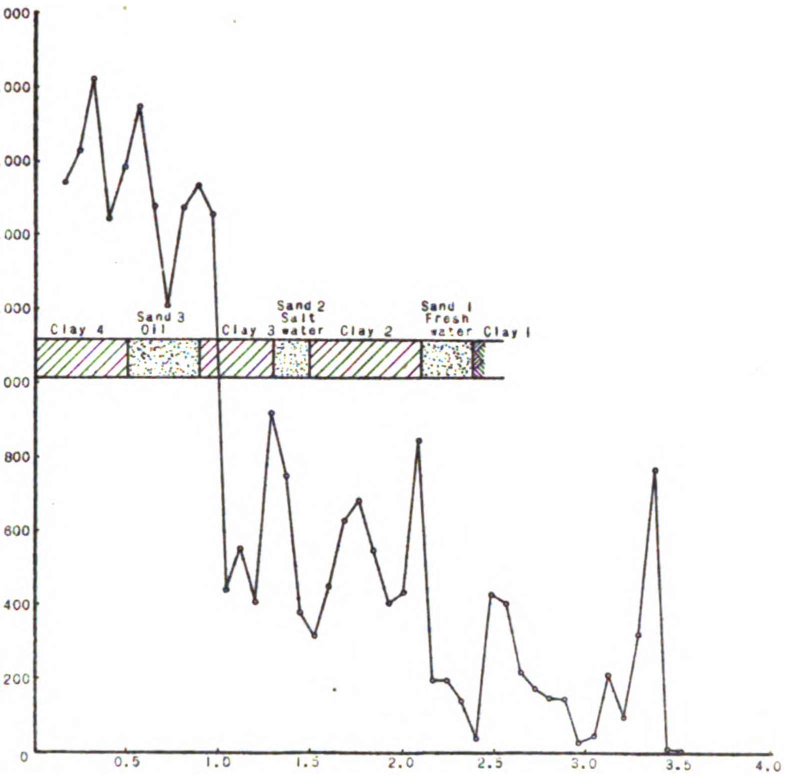

Figure 9.- Curve obtained on flat side of experimental block by the single-electrode, probe, using shells of constant thickness, following Schlumberger

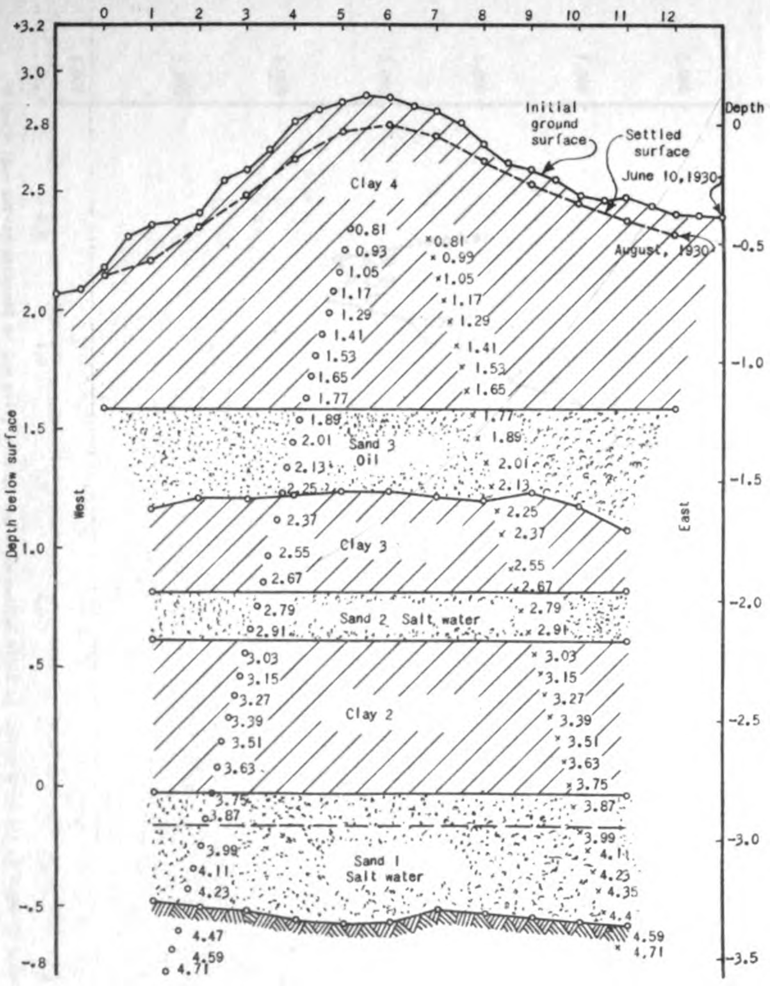

Figure 10.- Vertical section through hilly side of experimental block along line of measurement B

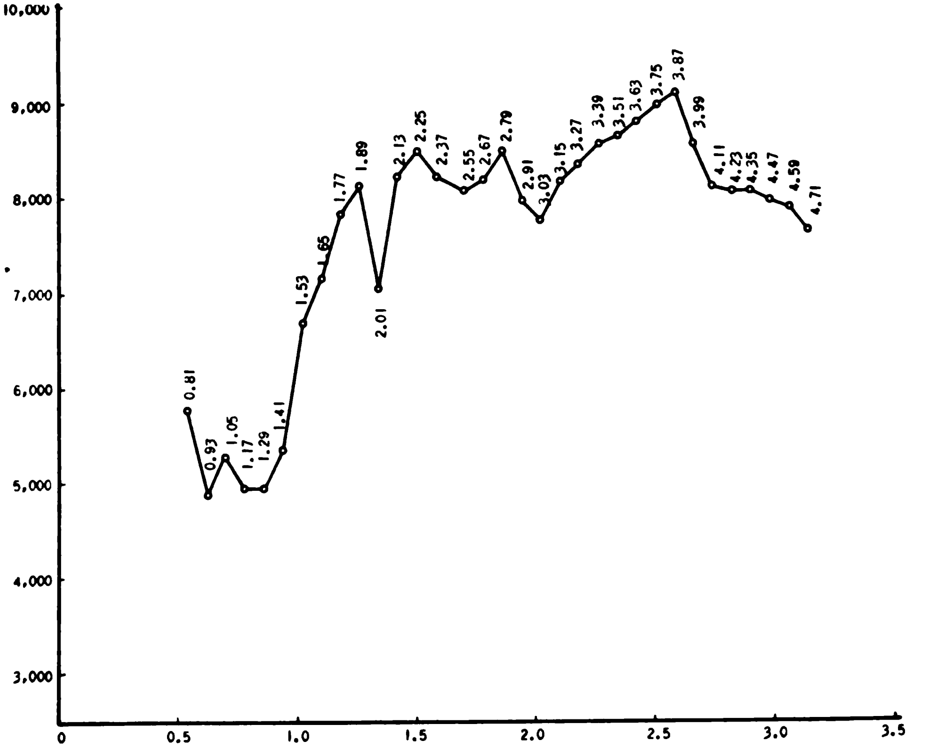

Figure 11.- Curves obtained on the hilly side of the experimental block by Lee's method of partitioning with direct current. West line

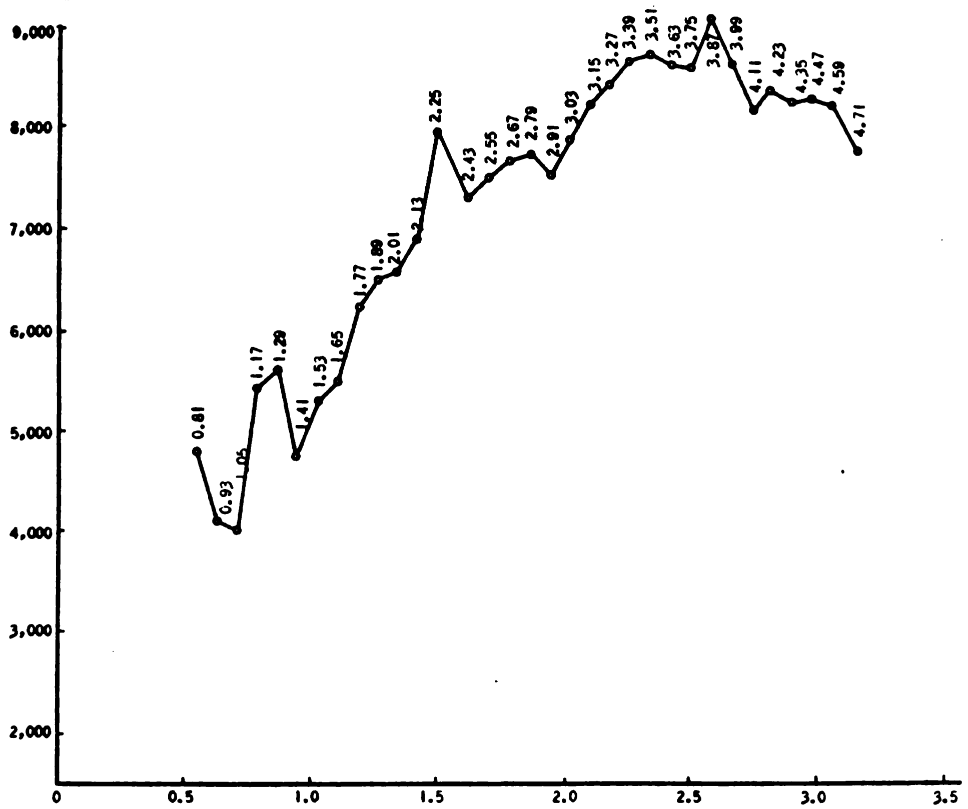

Figure 12.- Curves obtained on the hilly side of the experimental block by Lee's method of partitioning with direct current. East line

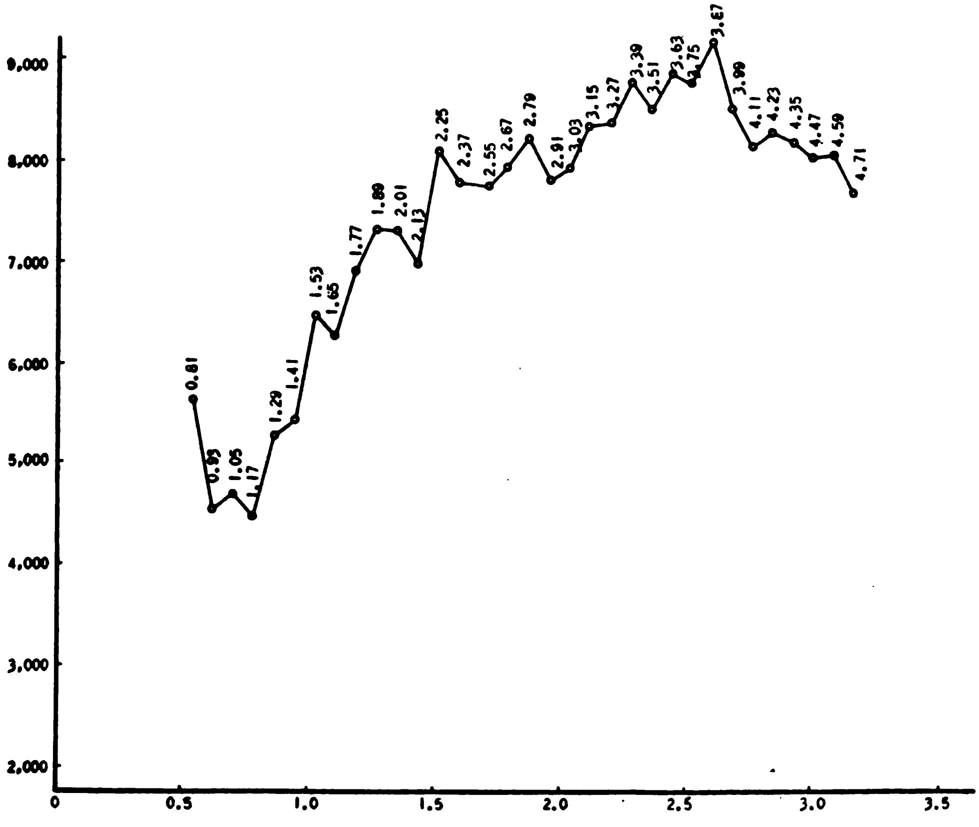

Figure 13.- Curves obtained on the hilly side of the experimental block by Wenner's method with direct current

series of contiguous, nonoverlapping shells of constant thickness, in this case 0.08 foot. The rapid variations and marked irregularity of the curve is its most marked feature. There is no apparent resemblance between this curve and that of Figure 8, nor is there much basis for interpretation. It is obvious from the curve that irregularities in surface resistivities are so great as to mask variations due to subsurface conditions. This experiment confirms the view long held by Lee that data obtained by the use of shells of constant thickness is too greatly affected by surface variations in resistivity to have any value in the interpretation of subsurface conditions.

MEASUREMENTS ON THE HILLY SIDE OF THE BEDS

The measurements discussed were all made on the flat side of the experimental beds. The remaining discussion will deal with measurements made on the hilly half of the experimental block, as shown in Figure 1.

Figure 10 gives a section through the artificial beds along the east-west line used in all the following experiments. The upper, solid line gives the surface of the beds as it appeared during the Lee and Wenner measurements. The lower, broken line gives the surface as it appeared during the single probe measurements.

As already noted, topographic variations need to be considered in interpreting resistivity measurements, especially in determining the depths attained. The chief purpose of the following experiments on the hilly half of the block was, first, to confirm more completely the conclusion that a topographic correction is required and, second, to determine its nature.

In view of the apparent exactness with which the value of $\underline{a} = 1/3\ C_1C_2$, (fig. 3) expresses the depth attained, as noted in the foregoing experiments with Lee's method of partitioning, it was assumed as a first approximation that the proper topographic correction would be obtained by plotting below each current stake position the corresponding value of $\underline{a}$. The points indicated by circles and cross marks in Figure 10 were obtained in this way, the numbers beside them again representing the distance of the corresponding current stake from the center. The correctness of this assumption stands or falls by the accuracy with which the points so located fit the curves obtained here by Lee's method, as discussed subsequently

Lee's Method of Partitioning

The curves obtained by the use of Lee's method on the hilly half are shown in Figures 11 and 12. The west line shown by the curve in Figure 13, reaches a maximum at the 2.25 point which corresponds exactly to the base of the oil sand as shown in Figure 10. There follows a drop through the moist Clay 3, with a rise to a second peak at 2.79, followed by a drop through the salt water of Sand 2 to a minimum at 3.03. From this point on it rises rapidly to a second peak at 3.87 in the dry upper portion just above the salt water in Sand 1. This is followed by a fall through the salt water, with a flattening out at 4.11, followed by a renewed drop when the clay base is reached at 4.35. The curve fits the points as plotted in Figure 10 with surprising accuracy. The only discrepancy, a slight one, is the apparent downward shift of the salt water in Sand 2. This is more probably due to a downward soaking of the salt water into the upper part of Clay 2, which had been considerably dried out and cracked before the sand was placed in it. In this way the salt water might easily have been lowered the 0.06 foot required. This would leave a thin dry zone at the top of the sand, thus accounting for the maximum at 2.79, and also would give raise to a saturated zone at the top of the underlying clay, thus accounting for the minimum at 3.03.

The east line, in Figure 12, rises also to a maximum at 2.25, indicating the base of the oil sand. This is followed by a drop into the moist Clay 3, whence the curve again rises to a maximum at 2.79, followed by a drop into the salt water minimum at 2.91. This time point 3.03 is definitely below the salt water zone. Clay 2 persists in its effect to 3.75, where we again get a rise to a maximum at 3.87 in the dry upper portion of Sand 1. This is followed by a drop into salt water and a flattening out at 4.11, as in the west curve. The break at 4.59 possibly indicates passage down into the basal clay. All points fit satisfactorily, with the possible exception of the oil maximum at 2.25. This point is apparently offset 0.05 foot.

The most important fact to be noted here is the accuracy with which the points of the curve coincide with the points plotted in Figure 10. It follows that the assumption on which they were based is probably correct. A topographic correction is thus necessary where the current electrodes are moved during measurements. The depth attained is further equal to a (= 1/3 C C) and should always be measured from the surface of the ground downward beneath the corresponding current stake position. This experiment indicates that the stratum reached is that lying at that depth at that point.

To refer all measurements to a fixed point, such as the center about which measurements are made, it is necessary to subtract algebraically from the depth, a, the difference in elevation between the fixed point and the current stake position, calling all higher elevations positive and all lower elevations negative. To determine the stratum penetrated it is also necessary to correct for the dip and strike of the beds between the two points.

Wenner Method

Figure 13 gives the results of measurements with Wenner's method at the same place and along the same line. Since the two curves obtained by the method of partitioning are so much alike, indicating a close similarity in the two halves of the field, it is not surprising that the Wenner curve is unusually clear-cut and resembles them closely. Even under these favorable conditions, however, it is less regular and clear-cut than the partitioning curves.

This method is subject, of course, to the same topographic corrections as Lee's method, with the added difficulty, however, that different corrections in the two halves of the field will frequently throw the corresponding hemispheres into different strata, thus still further confusing the curves. These errors for deep observations may become a critical factor.

Single-Electrode Probe

The curve in Figure 14 was obtained on the hilly half of the beds by the method of the single electrode probe, using overlapping shells in which a always equals 2b, utilizing the same line (line B, fig. 1) and center. The curve again presents difficulties of interpretation because of the variable relationship between plotted and true depth. The minimum at a depth of 0.40 foot is perhaps approximately at the base of Clay 4. The maximum at 0.72, or that perhaps between 0.96 and 1.04, appears to represent the base of the oil Sand 3. The minimum at 1.52 feet probably represents the base of the salt water in Sand 2. Contrary to the results of the curve shown in Figure 8, the plotted depth is here always too shallow and must always be multiplied by a factor greater than 1.0 to obtain the true depth. Again, however, the correction factor is not a constant, but a variable which appears to decrease with depth.

CONCLUSIONS

Of the various methods tried, Lee's method of partitioning gives the sharpest, most clear-cut, and most easily interpreted results. Wenner's method fails because it averages together the two usually quite dissimilar halves of the field. Lee's method of partitioning has the further advantage that it gives a simple depth relationship, which is a constant one. The depth to the stratum displaying the resistivity shown by a given point on the curve is in these experiments always equal to one-third the distance separating the current stakes for that point, as measured beneath the particular current stake position for that point. This relation does not appear to vary with changes in the resistivities of the beds penetrated - a rather surprising result since it was to be expected that the equipotential hemispheres would be very differently distorted by beds of different resistivities, with corresponding variations in the depth recorded.

In general the single-electrode probe gives less clear-cut results than the method of partitioning and has the further disadvantage of a variable ratio between the outer radius, $\underline{a}$, and the true depth.

The necessity for a topographic correction where current stakes are moved during measurements, as in the Lee and Wenner methods, is one of the important results of the present study. Since the hemispheres center about the current stakes and not about the center of measurement, measurements of depth must be made below the current stake. To refer all measurements to a fixed point, such as the center, differences of elevation between the fixed point and the current stake must be subtracted algebraically from the depth below the current stake, designating as "negative" all points below the center, or other fixed point, and those above as "positive." To correlate the stratum reached with those below the fixed point it is necessary to correct for the difference of elevation of the stratum between the fixed point and current stake. This may be easily calculated, if the strike and dip of the beds are known, from the formula

$$h = D \cos \beta \sin \delta,$$

where $\underline{h}$ is the difference in elevation desired, D is the distance between fixed point and current stake, δ is the angle of dip, and β is the azimuth angle between the dip-bearing and the bearing of the line joining current stake and fixed point. Nomographs for the graphic computation of depth to a stratum will be found in a paper by Mertie .

The stratum reached is always that lying at a depth $\underline{a} = 1/3\ C\ C$ below the current stake. This fact must always be borne in mind, since two factors, depth and the lateral position of the stake, are involved and must be considered for a proper interpretation of the data.

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6 - Mertie, J. B., jr., Graphic and Mechanical Computation of Thickness of Strata and Distance to a Stratum: U. S. Geol. Survey, Prof. Paper 129-C, 1922 pp. 39-52.

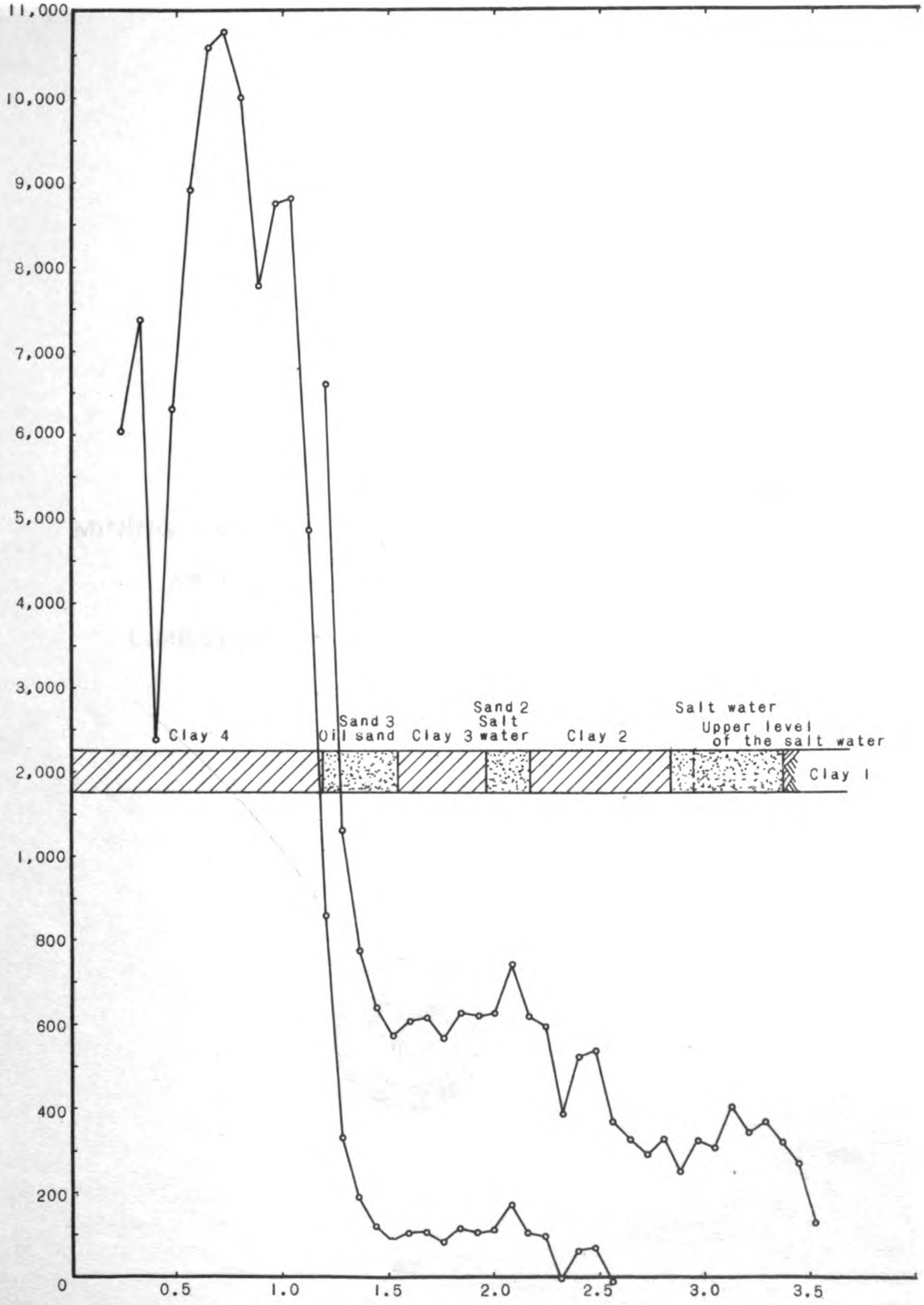

Figure 14.- Curves obtained on hilly side of the experimental blocks by the single-electrode probe, keeping a = 2 b